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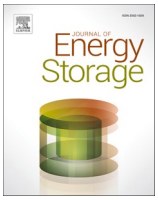

Trends and future perspectives on the integration of phase change materials in heat exchangers

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ABSTRACT

Traditional review papers provide mainly qualitative information, missing to show the volume, trends, and major contributions in a topic. In response to that, this paper asseses both quantitative and qualitative information regarding the implementation of thermal energy storage using phase change materials in heat exchangers. The data were retrieved from the Scopus database using specific queries relevant to the topic. To investigate the state-of-the-art and research gaps, a keywords analysis was carried out highlighting relevant connections among the major keywords. Moreover, a bibliometric analysis was performed to obtain the trends on the number of publications per year, type of document, authors, affiliation, geographical distribution, journals of publication, and subject areas of research. Based on the keywords and bibliometric analyses, this paper highlights the major contributions and research gaps on the topic.

1. Introduction

The UN 2030 agenda for sustainable development raises concerns on the increasing world energy demand and calls for solutions to reach sustainable and reliable energy goals [1]. These goals should tackle climate change and counteract with the overwhelming increase in the energy demand due to technology and comfort [2–4], especially because fossil fuels are the dominant energy source [3,5]. Indeed, to minimize environmental pollution as a goal to obtain a sustainable environment, the most promising solutions consist in improving the efficiencies of energy systems and/or maximizing the use of renewable energy sources. As a consequence, this may reduce the amount of fossil fuel consumption, as the primary energy source, thus reducing the carbon dioxide footprint. In response to these, thermal energy storage (TES) using phase change materials (PCM) is a promising solution to improve the performance of energy systems and to address the intermittency drawbacks of renewable energy sources. Moreover, the utilization of this technology has proven to contribute highly to reducing the carbon dioxide footprint [6].

The major advantages of PCMs are their high thermal energy storage density and ability to absorb or release thermal energy at a relatively constant temperature during the phase change [7]. However, the integration of PCM into an application is a challenge because of their low thermal conductivity. In that account, it is important to choose the right storage design/type from the most common storage designs/types used in practical applications [8]. To do this, besides the energy storage density, the charging and the discharging power of the PCM must be taken into account, which highly depend on the type of heat transfer considered.

In the first storage type, the heat transfer fluid is also the storage medium, e.g. slurry, a mixture of HTF and microencapsulated PCM [9]. The second storage type is the storage with heat transfer on the TES surface, characterised by low charging and discharging power. The third type comprises storages with heat transfer on the internal heat transfer surfaces, e.g. heat exchanger type [10]. In this type, the PCM is contained in a vessel whereby the charging and discharging of the energy is through the HTF fluid. It is the most advantageous storage type, and has a wide range of applications due to its flexibility in control and high heat transfer coefficient, gaining more interest among the researchers [11–13]. It allows an improvement of the heat transfer coeficient by employing fins, and/or varying the velocity of the HTF fluid, using pumps or fans [14]. Related to the advantages mentioned above, this storage type gained more interest on applications operating in a closed loop like refrigeration and air-conditioning systems. However, in spite of the large volume of research papers on the topic, there are no detailed research papers containing both quantitative and qualitative information on the topic. Hereby, quantitative information refers to the volume of the bibliometric data which is enriched with statistical information, while the qualitative information refers to the subtopics/keywords studied in a topic.

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Table 1
Queries on inplementation of PCM in a HEX (Query1) and at the evaporator (Query 2).

Query 1	Query 2
TITLE-ABS-KEY (((pcm OR "Phase chang* Material*" OR "latent energy Storag*" OR "latent heat Storag*") AND "heat exchanger"))	TITLE-ABS-KEY ((((pcm OR "Phase chang* Material*" OR "latent energy Storag*" OR "latent heat Storag*") AND "heat exchanger")) AND evaporator*)

To effectively examine the state-of-the-art, major contributions, research gaps, and future perspectives focusing on the heat exchanger storage type, keywords and bibliometric analyses methods were employed. Bibliometric analysis is a statistical evaluation of scientific articles, books, or book chapters, which has gained interest in recent years especially in scientific community [15–18], while, a keywords analysis determines and highlights the relationship among the potential keywords/subtopics in study of a topic. Keywords are paramount tools in search engines, as they are used in a web form to connect and retrieve information accordingly. However, evaluating the occurrences and relationships among keywords is not an easy task to perform manually. Therefore, to perform an accurate and precise study of the keywords, software like VOSviewer [19] can be used. VOSviewer is an open-access software for constructing and visualizing bibliometric data in networks showing the occurrence and correlation among keywords in the study.

This paper assesses for the first time the literature on PCM implementation in heat exchanger (HEX), connecting quantitative and qualitative information, with the perspective to inspire the alignment of future studies. To perform this task, a first general query was used to retrieve the documents with a focus on PCM implementation in a HEX. As a consequence of a research gap obtained from the first query, a second query was formulated, which subsequently retrieved documents mostly related to refrigeration and air-conditioning systems. Using the keywords analysis method, the paper evaluates the relationships/links, the magnitude and the trend of study of the subtopics. Finally, the bibliometric analysis method was used to analyse and compare the major contributions resulting from applying both queries, based on number of publications, trends, journals, authorship and affiliations, geographical distribution, type of document, and subject area.

2. Methodology

In this paper, bibliometric and keywords analyses methods were used to study the state-of-the-art, research gaps, and the potential contributions to the implementation of PCM in a HEX. The data in this study were retrieved from Scopus database for all types of documents, throughout the entire time span until 6 April 2020 (the day of access to Scopus database), based on Title-Abstract-Keywords fields. This means that the queries captured documents containing the keywords search strings in either the title, the abstract or the keywords section, while avoiding to search keywords in the introduction section, which normally contain general information, and could provide a wrong data sample for the analysis. The study was based on Scopus database because it is reliant and contains the most updated documents. Indeed, Cabeza et al. [15] performed a comparative analysis between Web of Science and Scopus databases on energy efficiency and climate impact in buildings and reported that the Scopus database had more and updated data on scientific topics compared to other databases. The same authors also mentioned that other databases like Google Scholar do not have enough and reliable documents for such an analysis in engineering fields.

A key aspect to extract all significant documents relevant to the topic studied is to use the right query. To realize the bibliometric analysis, the two queries shown in Table 1 were formulated and used to capture the documents published on PCM implementation in a HEX. The first query, Query 1, extracted all documents concerning PCM implementation in a HEX, whereas the second query, Query 2, retrieved documents linked to PCM implementation at the evaporator, with the objective to assess in depth the literature gap obtained. The only difference between the two queries is that the second query contains “evaporator” as an additional word. Hereby the term “evaporator” was chosen because it is the main heat exchanger, which has gained interest among the researchers, to implement PCM in refrigeration and air-conditioning systems, especially for low temperature applications [20–23]. An attempt to include

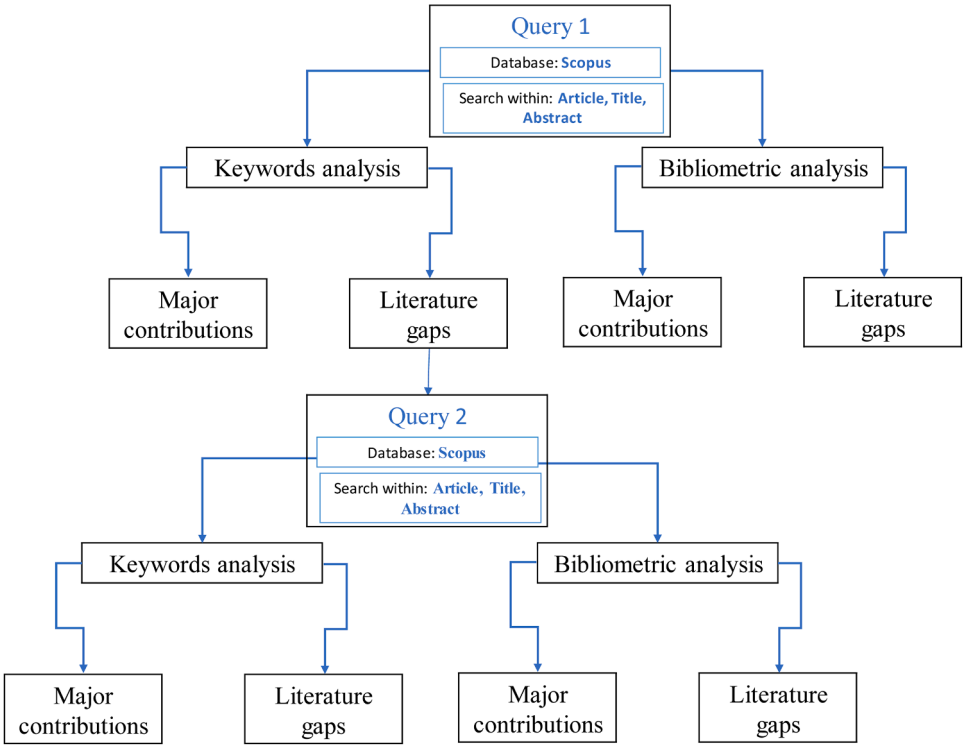

Fig. 1. An overview of the methodology applied to analyse the implementation of PCM in HEX.

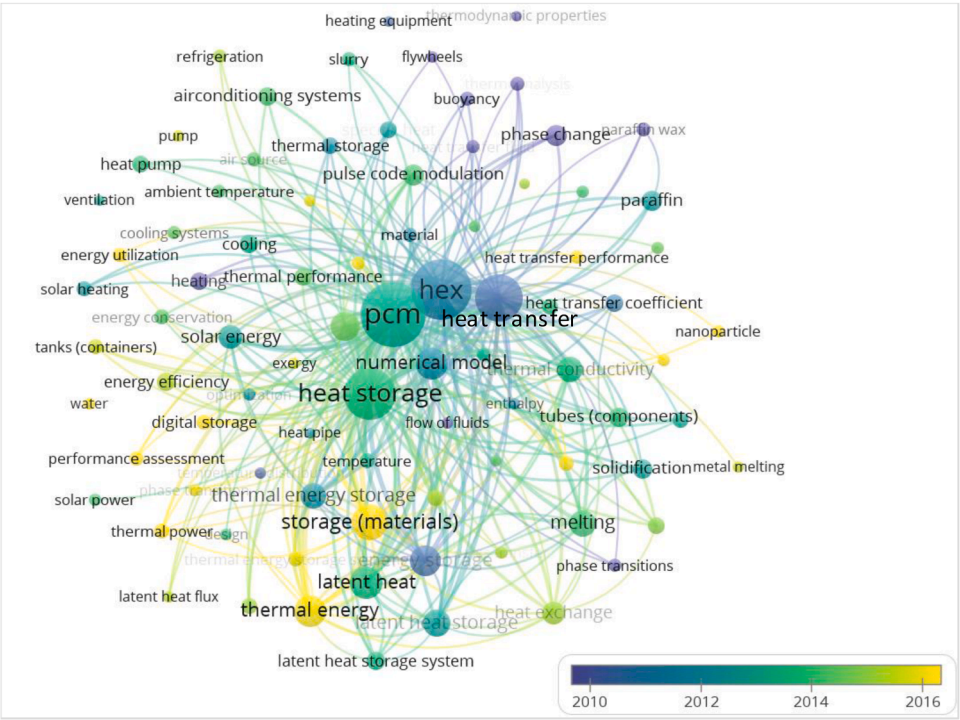

Fig. 2. Global overview of the major keywords used on PCM implementation in a HEX.

"refrigeration" and "air-conditioning" keyword into the search string was carried out, and it was found out that there were many papers which were not related to the integration of PCM in a heat exchanger.

To analyse the two queries, a similar methodology was carried out for both of them following the flow shown in Fig. 1. The literature gaps obtained from the keywords analysis from Query 1 were further studied using Query 2.

To investigate the most occurring keywords and the relationship among each other, a keywords analysis was performed using the software VOSviewer. For a comprehensive visualization of the most relevant keywords in each query, a trial and error approach was used until a satisfying level of clarity was obtained. A sufficient level of clarity was defined when the information on the figure could clearly be identified and the focus of the topic was not distorted. Hereby, for Query 1, the analysis was limited to keywords with minimum occurrence of 30, whereas for Query 2, the query was limited to keywords with minimum occurrence of 5. Moreover, to highlight the trends on publications related to the topic with link to respective subtopics, overlay visualizations of the major keywords are presented using spheres and lines with different colours. The size of a sphere is used to present the magnitude of occurrence of a keyword while the lines and the distance among each keyword present the link or relationships among keywords. The links provide information on how much the subtopics/keywords are studied together. Moreover, the colours present the trends of publications from dark blue, as the oldest, to green and, finally, yellow as the most recent studied subtopics/keywords. To assess the statistical information in the documents, a bibliometric analysis method was used to investigate the type of publication, the subject area of publication, the publication journals, the authors, the affiliations, the geographical distribution of publications, and the trends of publications. The study is accompanied with an overview of the major subtopics retrieved by the keywords and bibliometric analyses, and highlighting the most recent papers from 2015 onwards, which mostly addressed the subtopic/keyword analysed.

3. Results

This section presents the results of the bibliometric and keywords analyses of the data extracted from Scopus database for the two queries. Query 1 captured 1225 documents published on PCM or latent heat/energy storage implementation into a HEX. After analysing and determining the research gap in the first query, a second query, Query 2, was used, which retrieved 46 documents, representing 3.8% of the documents in Query 1.

3.1. Keywords analysis on PCM implementation in a HEX (Query 1)

Regarding the keywords analysis using VOSviewer, a total of 6560 keywords are available in the Query 1, whereby only 86 keywords occurring more than 30 times are presented. Moreover, to visualize the keywords in a comprehensive way, VOSviewer allows to limit the number of links, and therefore the results presented hereby are limited to a maximum of 400 lines/links. Indeed, the keywords and links presented in the figures, represent the most occurring keywords and the strongest links respectively. More details on the number of occurrences and links are also provided to enable a better interpretation of the results.

Fig. 2 shows an overlay visualization of the global literature map of the major keywords used to study PCM implementation into a HEX. From the documents captured, "PCM" and "HEX" are seen to have the most occurrences and links reported by the size and distance between their spheres, as expected from the query used. However, the major subtopics linking PCM with a HEX were observed to be "heat transfer" and "heat storage" with 526 and 623 number of occurrences, respectively. Hereby, "heat transfer" is seen closer to "HEX" with 85 links while "heat storage" is seen closer to "PCM" also with 85 links, meaning that the studies on PCM mainly focus on "heat storage" while the studies on a HEX mainly focus on "heat transfer". The keywords in the peripheries of the figure represent those keywords/subtopics with the least co-occurrence with PCM and HEX, which provide information on the literature gap. Regarding trends, the studies linking PCM and a HEX started with a major focus on "heat transfer", then "heat storage", and recently highly concentrated on "storage (materials)."

The same Fig. 2 shows that the current trend, from 2015 onwards, in the study focuses on "nanoparticles," "heat transfer performance,"

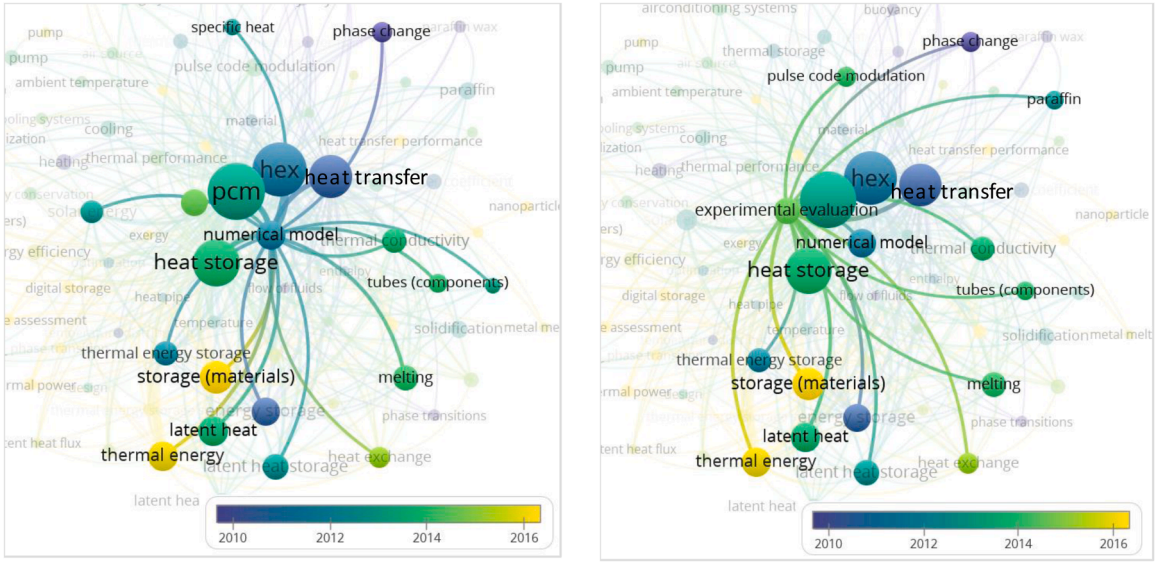

Fig. 3. Approach used in implementation of PCM in a HEX: (a) numerical, (b) experimental.

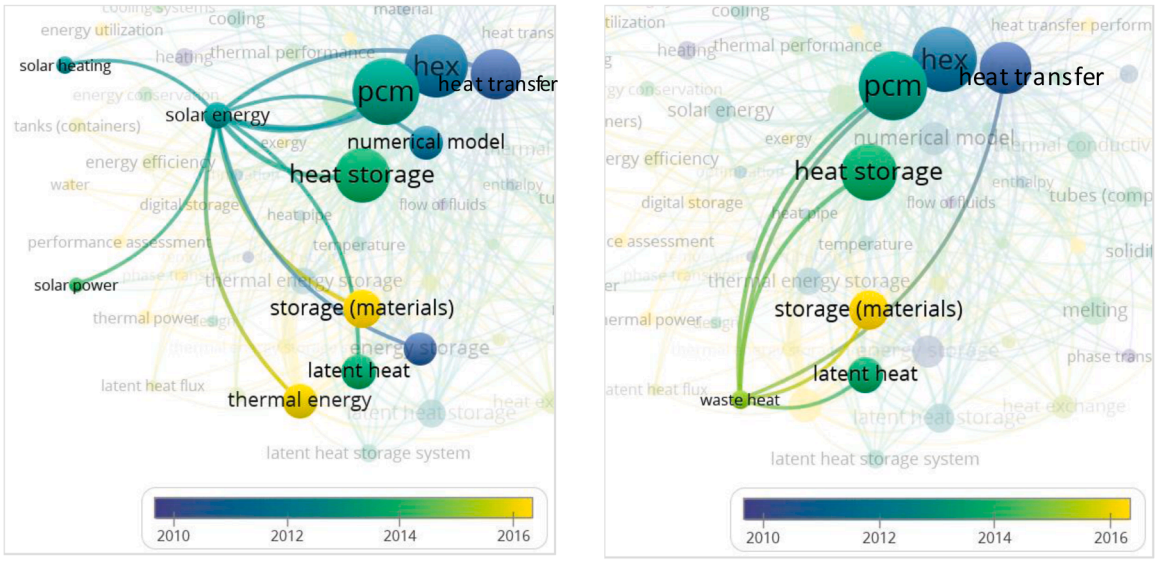

Fig. 4. Energy source utilized: (a) solar energy, (b) waste heat.

"performance assessment," and "energy utilization." The current studies on "nanoparticles" are performed with an objective to enhance the solidification of PCM in a HEX. Mahdi et al. [24] performed a numerial model of a triplex-tube heat exchanger containing PCM, and reported an enhancement of the solidification process even by adding 1% or 2% of Al_2O_3 nanoparticles. Moreover, Sheikholeslami et al. [25] numerically studied the inclusion of CuO nanoparticles in a finned heat exchanger, to enhance the discharging process, and reported that the shape/geometry of the nanoparticles has an influence on the transient process. Regarding "heat transfer performance," Jingzhi et al. [26] recently performed a numerical model investigating the heat storage process on spiral groove tubes. The model depicted an enhancement in heat transfer while using spiral groove tubes than with smooth tubes. Concerning "performance assessment," Sodhi et al. [27] recently performed an assessment of heat transfer characteristics of a latent heat thermal energy storage (LHTES) system using a multi-tube HEX. The results showed that increasing the number of tubes, the heat flux distribution was improved and the duration of charging and discharging processes was reduced. Furthermore, for "energy utilization", Maccarini et al. [28] developed a model of PCM-based HEX coupled with a novel HVAC system for simultaneous heating and cooling of buildings. The results showed that 67% annual primary energy savings can be achieved compared to the baseline thermal plant configuration.

The implementation of PCM in a HEX is commonly studied either through a numerical model approach or an experimental one. Fig. 3 compares the two approaches based on the number of occurrences, links and trends in study of the topic. Both approaches were observed to be linked to 85 other keywords and with very similar occurrence; i.e. 235 occurrences for numerical model approach, and 200 occurrences for experimental evaluation approach. Furthermore, this figure also shows

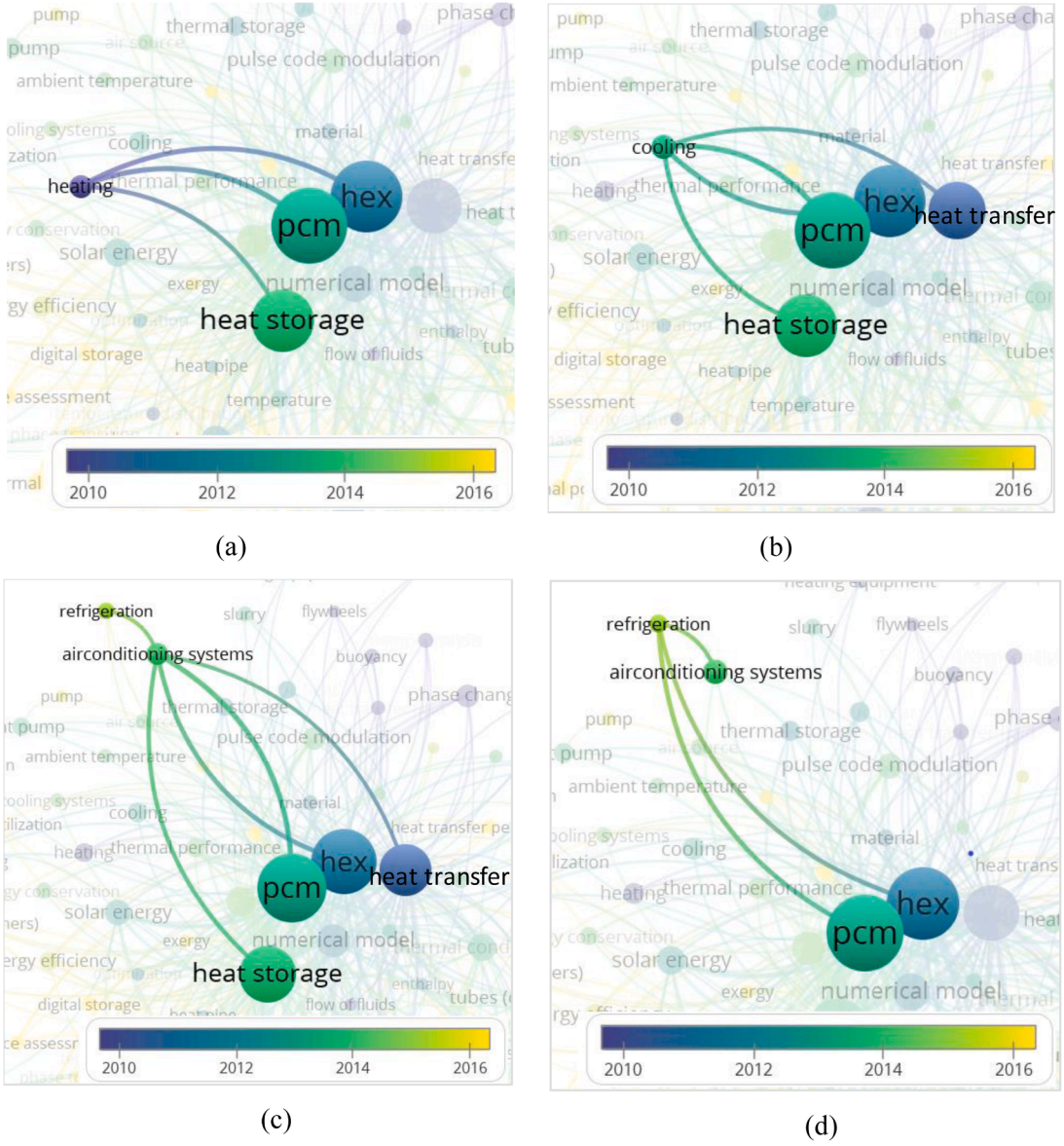

Fig. 5. Applications in focus during implementation of PCM in a HEX: (a) heating, (b) cooling, (c) air-conditioning, and (d) refrigeration.

that the study on the topic started with the numerical model approach and recently has changed its trend to an experimental evaluation approach.

Taking into account the heat source/sink, thermal energy technologies are mainly used to recover waste heat and solar energy. Fig. 4 provides details on studies related to recovery of waste heat and solar energy in the implementation of PCM into a HEX. Solar energy has 141 occurrences linked to 84 keywords/subtopics, while waste heat has 60 occurrences linked to 75 keywords. Moreover, the appearance of "solar energy" in Fig. 2 is more centric than "waste heat", which is observed at the peripheries. This means that solar energy has obtained more interest among researchers than waste heat in the study of the topic, though both are used in the same applications. However, from 2015 onwards, the newest trend on PCM implementation in a HEX focusses more on recovery of "waste heat" than on "solar energy".

The most prominent applications on the implementation of PCM in a HEX are highlighted in Fig. 5, such as heating, cooling, air-conditioning, and refrigeration. The trends on studying the topic started with focus on heating, then cooling, and mostly recently in air-conditioning and refrigeration applications. Hereby, "heating", "cooling", "air-conditioning", and "refrigeration" have 78, 85, 88, and 47 occurrences, which are linked to 82, 81, 80, and 63 keywords, respectively. As shown in Fig. 2, heating and cooling are more centric than air-conditioning and refrigeration, although they are similarly linked to other subtopics. For that reason, it is interesting to have a detailed analysis (available in Section 3.2), with focus on air-conditioning and refrigeration applications, showing the state-of-the-art, and the literature gaps.

3.2. *Keywords analysis on PCM implementation at the evaporator (Query 2)*

Using "VOSviewer" for the keywords analysis, Query 2 was observed to contain a total of 545 keywords and, after limiting the keywords to best possible clarity, 18 keywords were presented on the global literature map. The query captured documents relevant to the implementation of PCM at the evaporator.

Fig. 6 shows an overlay visualization of the global literature map highlighting the keywords that mostly appear in the literature regarding the implementation of PCM at the evaporator (Query 2). This trend started with "thermal control systems" with the objective of "temperature control" to recently focus on "energy efficiency" and "storage materials". Based on "thermal control systems," the first research was realized by Leimkuehler et al. [29], by developing an ice PCM heat

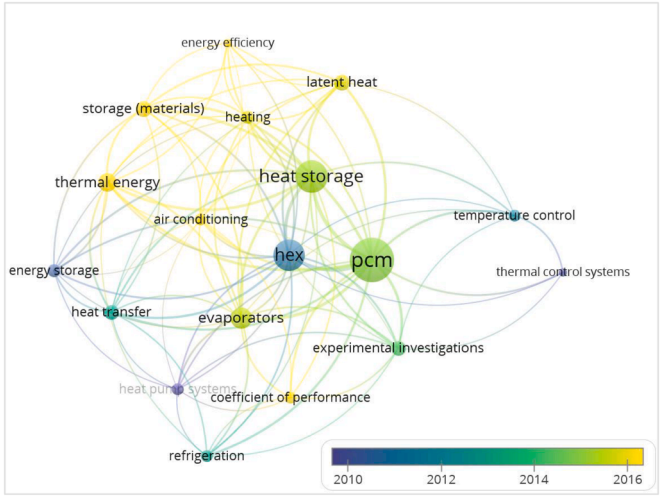

Fig. 6. Global overview of the major keywords used on implementation of PCM at the evaporator.

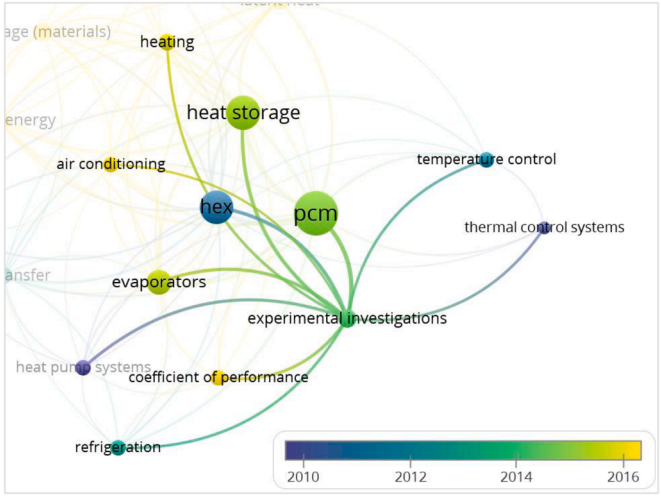

Fig. 7. Experimental evaluation as the approach used in studying the topic.

exchanger, and experimentally investigating failure mechanism, which could be a result of expansion of PCM during the freezing process. The study was performed with an objective to construct systems with significant reduced mass for space exploration by taking advantage of PCM high energy density and isothermal energy liberation/release.

As highlighted in Fig. 7, the keywords analysis shows that the most widely used method of studying PCM implementation at the evaporator is through experimental evaluation/investigation. It is observed to contain 9 occurrences, which are linked to 16 keywords. However, there is no evidence of any numerical investigations even on the global literature map in Fig. 6. In that account, numerical investigation contains less than five occurrences, which is the minimum number of occurences for a keyword to be presented on the global literature map.

Fig. 8 highlights the keywords that represent the major applications/systems linked to the implementation of PCM at the evaporator. A similar number of occurrences and links is observed among the major applications, i.e. air conditioning, refrigeration, and heat pump systems. While each of them has seven occurrences, “air-conditioning” is linked to 15 keywords, “heat pump systems” are linked to 14 keywords, and “refrigeration” to 12 keywords.

Regarding trends, the implementation of PCM at the evaporator started in “heat pump systems”, followed by “refrigeration” and, recently, highly focusing on “air-conditioning”. To take advantage of the PCM technology in air-conditioning systems, Lee [30] experimentally investigated the integration of cold storage HEX into the evaporator of an automobile air-conditioning system to solve thermal discomfort in the cabin whenever the engine goes on standby. The solution proposed was concluded as an effective solution for maintaining thermal comfort in vehicles using ISG (Idle Stop Go) system, especially during short engine stops. Moreover, Javani et al. [31] studied the optimization of thermal management systems using PCM, for hybrid electric vehicles, by integrating PCM shell and tube HEX parallel to an evaporator in a refrigeration cycle. The study reported a higher exergy efficiency of the overall system, which was contributed by increasing PCM mass fraction. Another study taking advantage of PCM was performed by Copertaro et al. [32] on integrating PCM-air-heat exchanger near the evaporator of a refrigeration systems in a cold room to reduce the number of compressor ON and OFF cycles. The study reported a reduction to less than half of the number of ON and OFF of compressor and about 16% energy savings achievement of the system. For heat pump systems, PCM is used at the low pressure side to increase the performance of the system [33] or to solve frosting problem on the external HEX of heat pumps when exposed to very low temperatures [34].

3.3. Bibliometric analysis on PCM implementation in a HEX and at the evaporator

Fig. 9 shows the publications trends on the implementation of PCM in a HEX (in blue) and PCM implementation at the evaporator (in orange). Regarding the implementation of PCM in a HEX (Query 1), Segut et al. [35] published the first paper on the topic in 1966 on the design of a HEX with latent heat storage working with molten salt-oil in direct contact. Another publication on the topic in the same year was by Brejon and Marchio [36] on the integration of a cold latent heat storage into a storage system by heat pump. There were no other publications on the topic until 1975 when Lorsch et al. [37] published on thermal energy storage for solar heating and off-peak air conditioning. Between 1975 and 2005 there were less than 10 publications each year. However, in the last ten years, there is a high interest and increase in the number of publications on the topic.

Regarding the implementation of PCM at the evaporator (Query 2), the first document was that published in 1966 on insertion of a cold latent heat storage unit into a storage system using a heat pump [36]. However, the research was nearly non-existent for 40 years with a total of about 5 publications until 2007. Comparing the two queries, there was a similar trend, with a first peak in 2010 and a drastic fall until 2012 to increase again in 2019. In the figure, the trend of the publications is presented on annual base for all time span until the end of 2019. However, in the first months of the year 2020, until 6 April 2020, the day of retrieval of the documents, there were 55 and 2 documents captured by Query 1 and Query 2, respectively.

The type and number of citations are parameters commonly used to provide an insight of the weight and the contribution of a document. Fig. 10a shows the distribution by type of documents available on the PCM implementation in a HEX. Journal papers are accounting for 64% of the total publications, followed by conference papers (29%), and conference review papers (3%). In Query 1, the top three most cited documents on PCM implementation in a HEX [38–40] have 1010 citations, 378 citations, and 342 citations, respectively.

The distribution based on the type of documents available on the implementation of PCM at evaporator (Query 2) is shown in Fig. 10b. Hereby, journal papers account for 59% of the total documents, followed by conference papers (30%) and conference review papers (9%). Here, the top three documents that focus on the implementation of PCM at the evaporator [20,34,41], have 51 citations the first one, and 39 citations both the second and the third ones, as retrieved on 6 April 2020.

The presentation of publications based on a geographical distribution highlights the concentration of research on the topic in the world. Fig. 11a presents the number of publications and density of publications

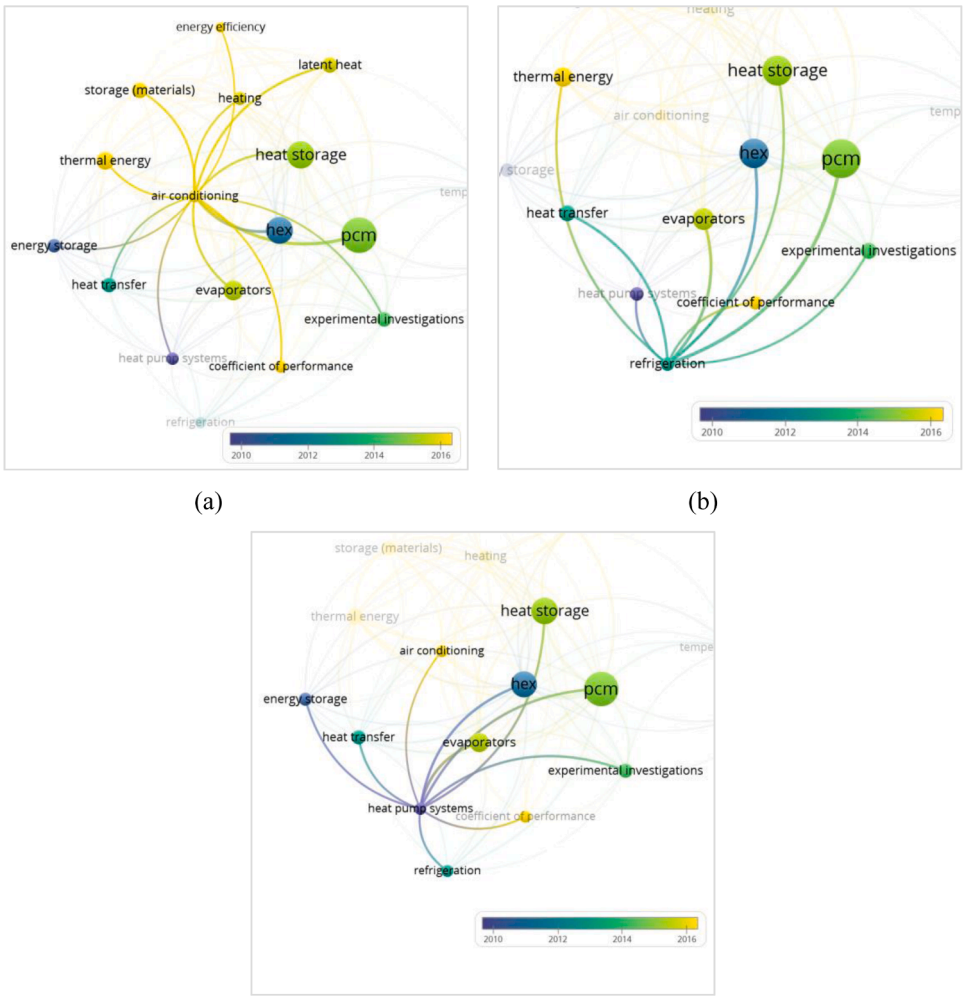

Fig. 8. Application/systems in study: (a) air conditioning, (b) refrigeration, and (c) heat pump systems.

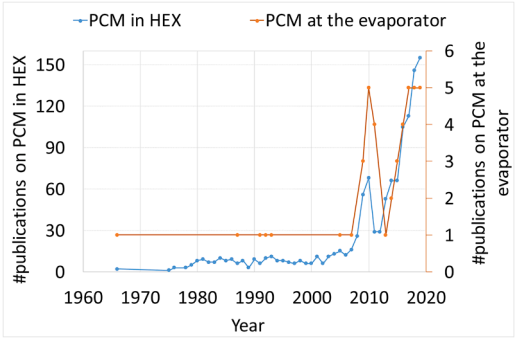

Fig. 9. Trends in publications on PCM implementation in a HEX (Query 1) and at the evaporator (Query 2).

of the top territories/countries where research documents on the PCM implementation in a HEX (Query 1) were published. The top three territories/countries with most publications on the topic are China with 224 documents, followed by the United States with 172 documents, and India with 88. However, considering the density of publications, Canada is at the top with about two publications per million inhabitants [42], followed by Spain and the United Kingdom.

Fig. 11b shows the top territories/countries carrying out research on PCM at the evaporator (Query 2). The United States is the first with 8 documents, followed by the United Kingdom with 5 documents. The other territories/countries have 3 or less documents on this field. When normalized, Austria is at the top with 0.23 publications per million inhabitants, a value that is still quite low and showing a prominent gap in the research field.

The evaluation of the publications based on the affiliation of the researchers can help to identify institutes or research groups working on similar topics encouraging partnership and accelerating the output of research. Fig. 12a shows the affiliation of authors with documents published on the implementation of PCM in a HEX (Query 1). The three prominent institutes are Babol Noshirvani University of Technology from Iran, the Ministry of Education of China from China, and Concordia University from Canada, each with at least 22 documents published on the topic.

Likewise, Fig. 12b presents the affiliation of authors with documents published on the implementation of PCM at the evaporator (Query 2). Practically, it is only NASA Johnson Space Center with more than two publications in the field. This low number of publications in all the institutes on this topic manifests the literature gap in the field.

Certainly, providing information about the researchers with the most documents in the research field acknowledges their contributions and may help new researchers to determine the experts for any consultancy. Table 2 shows the top researchers with more than 10 documents published on PCM implementation into a HEX. The top three researchers are Seiyed Hosseini from Iran, Luisa F. Cabeza from Spain, and Rasool Bahrampoury from Iran, with 22, 21, and 18 documents, respectively. Luisa F.

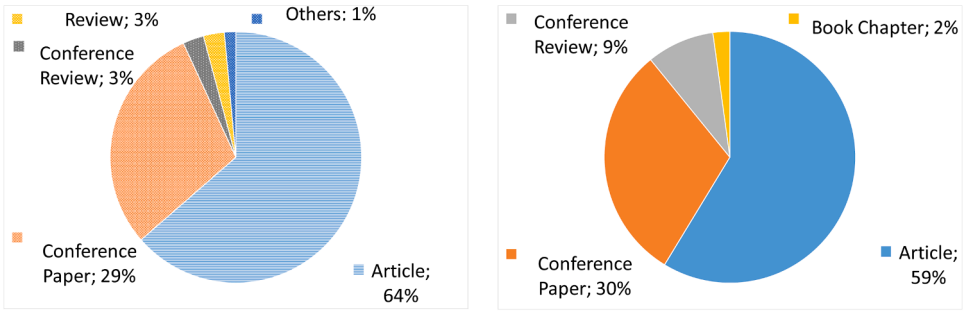

Fig. 10. Type of documents of publications: (a) PCM in a HEX (Query 1) and (b) PCM implementation at the evaporator (Query 2).

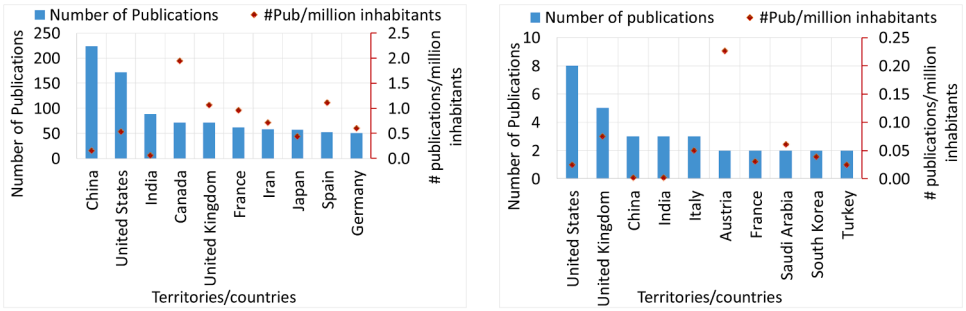

Fig. 11. Geographical distribution of the publications: (a) PCM in a HEX (Query 1), (b) PCM at the evaporator (Query 2).

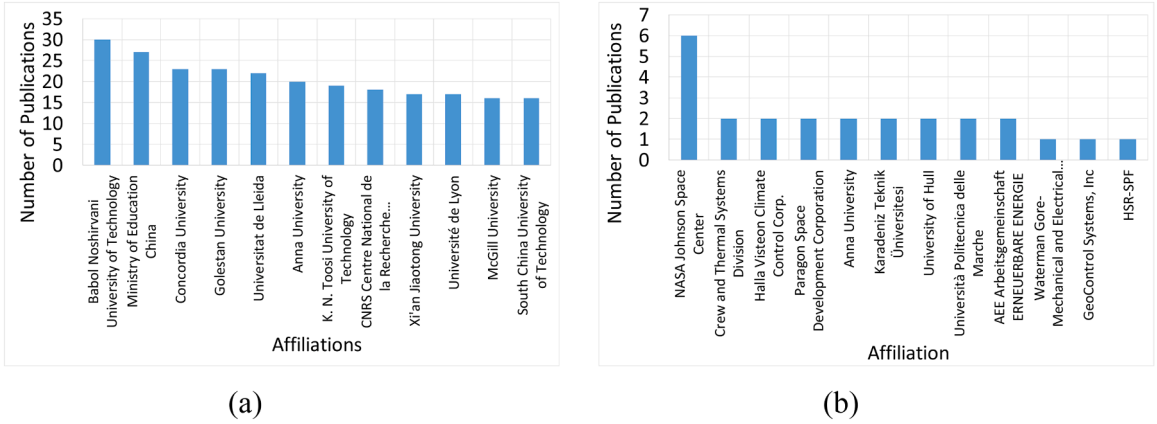

Fig. 12. Affiliation of authors with publications on the topic: (a) PCM in a HEX (Query 1), (b) PCM at the evaporator (Query 2).

Cabeza has more than 10 years of expertise on this topic, which is evident from the first document published in 2009 on experimental evaluation of commercial HEX for use as PCM thermal storage systems [14], and the last document published recently in 2020 on the evaluation of the state of charge of PCM in a TES tank [43]. Seiyed Hosseini published the first document in 2012 [44] and the last one in 2020 [46], mostly working on the implementation of PCM into shell and tube HEX. However, most of the documents published by Rasool Bahrampoury co-authored Seiyed Hosseini (e.g. [45]), which imply a close link of collaboration.

Table 3 shows that the implementation of PCM at the evaporator (Query 2) is not widely studied. Other than Ryan Stephan from USA who has five documents (four conference papers and one journal paper), the other authors have published two or less documents. Moreover, from the captured documents, Ryan Stephan is observed to have less experience on the topic in comparison to the top authors of documents captured by Query 1.

Fig. 13a shows the journals with more publications on the implementation of PCM in a HEX (Query 1) containing at least 20 documents. Applied Thermal Engineering is the top journal publishing on this research field, which has about two times more publications on this topic than the second journal, Energy Conversion and Management. The rest of the top ten journals have a comparatively similar number of documents on the field ranging from 50 to 20. Most of the documents in the study were published by reputable journals with an impact factor higher than 3.8 according to the 2018 Journal Citation Report.

Similarly, Fig. 13b shows the journals with the most publications on the implementation of PCM at the evaporator (Query 2). Again, the most used journal is Applied Thermal Engineering, followed by Energy, while all the other journals contain a relatively similar number of publications. Likewise, about half of the documents are published in top-ranking

Table 2
Authors of publications on PCM implementation in a HEX (Query 1).

	Query 1 Author	#Publications	Affiliation	Country
1	Seiyed Mohammad Javad Hosseini	22	Golestan University	Iran
2	Luisa F. Cabeza	21	Universitat de Lleida	Spain
3	Rasool Bahrampoury	18	Toosi University of Technology	Iran
4	Ali Akbar Ranjbar	16	Babol Noshirvani University of Technology	Iran
5	Fariborz Haghighat	13	Concordia University	Canada
6	Masoumeh Rahimi	13	Golestan University	Iran
7	Sohif Mat	12	University of Kebangsaan Malaysia	Malaysia
8	Kamaruzzaman Sopian	12	University of Kebangsaan Malaysia	Malaysia
9	Frank Bruno	10	University of South Australia	Australia
10	Pablo Dolado	10	Universidad de Zaragoza	Spain

Table 3
Authors of publications on PCM implementation at the evaporator.

	Query 2 Author	#publications	Affiliation	Country
1	Ryan Stephan	5	NASA	USA
2	Teoman Ayhan	2	Karadeniz Technical university	Turkey
3	Benedetta Copertaro	2	Universita Politecnica delle Marche	Italy
4	Roberto Fioretti	2	Universita Politecnica delle Marche	Italy
5	Kamil Kaygusuz	2	Karadeniz Technical university	Turkey
6	Paolo Principi	2	Universita Politecnica delle Marche	Italy
7	Min Yu	2	University of Hull	UK
8	Xudong Zhao	2	University of Hull	UK
9	Jinzhi Zhou	2	University of Hull	UK
10	Edacherian Abhilash	1	King Khalid University	Saudi Arabia

journals with an impact factor higher than 3.8.

The classification of documents retrieved using Query 1 is presented in Fig. 14a. The top three subject areas of publishing on PCM implementation in a HEX are engineering with 32% of the documents, energy with 25%, and physics and astronomy with 12%. Other subject areas with publications on the topic are material science, chemical engineering, and environmental science with about 8% each. Nonetheless, the sum of all other subject areas not mentioned above is 189 documents, which is about 8% of the total publications.

Considering publications retrieved using Query 2, shown in Fig. 14b, it is observed that the research is more concentrated in engineering with 42% of the total publications, followed by energy with 22%, and environmental sciences with 19%. The remaining subject areas of study have 13 documents, which cover only 17% of the total number of publications.

4. Discussion

The formulation of the query to retrieve documents is fundamental to all the study. Its validity and significance on the topic should be ensured so as documents relevant to the particular research are captured thus providing a clear picture of the state-of-the-art. In this study, using the keywords analysis method, showed that both queries had a high occurrence and correlation among the main keywords, hence proving its high relevance and significance to the study. However, care must be taken to ensure the validity of the queries used for such an analysis in future studies.

From the literature analysis showed above, both the research on the implementation of PCM into a HEX (Query 1) and at the evaporator (Query 2) started in 1966 but since then, only a small portion has focused on PCM implementation at the evaporator, as observed to take only 3.8% of the total number of documents. After the first publication, research on PCM implementation at the evaporator was nearly non-existent for about 40 years. Research trends for both cases are similar, with the first peak in 2010, then dropping and finally rising again and obtaining the second peak in 2019. Though not documented, it can be debated that the global affairs and policy targets can highly influence research outputs. In that respect, the peaks in 2010 and 2019 may have been attributed by 2010 and 2020 funding targets and the drop around 2012 may be argued to be an outcome of 2006–2008 economic crisis. However, in 2019 only 5 documents of the total of 155 documents published on PCM implementation in a HEX (Query 1), focus on PCM implementation at the evaporator (Query 2), accounting for only 2.1%.

The documents are published in reputable journals, mostly with an impact factor above 3.8, whereby Applied Thermal Engineering is leading for both queries. Moreover, the documents are mostly published as journal papers, accounting for 64% and 60%, and as conference papers as about 30% and 31%, and based mainly on engineering as the main subject area of publication with 32% and 42% of the total documents, for the first and second query, respectively. However, the low citation number of documents from Query 2, compared to the studies from Query 1, prevails an insight of the low input provided to the research focusing on the implementation of PCM at the evaporator.

Classifying the publications output based on the geographical locations/positions highlight the areas where the research is concentrated

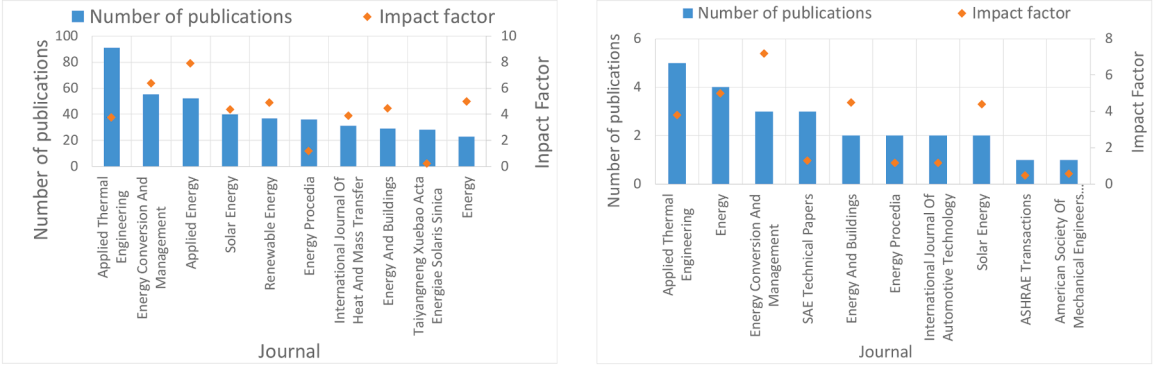

Fig. 13. Journals used for publications: (a) PCM in a HEX (Query 1), (b) PCM at the evaporator (Query 2)

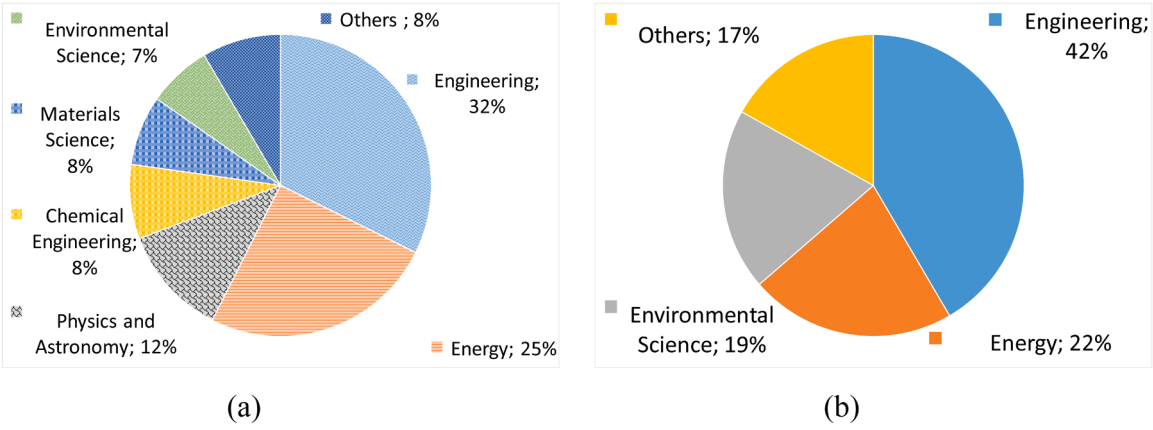

Fig. 14. Publications by subject area: (a) PCM in a HEX (Query 1), (b) PCM at the evaporator (Query 2).

and areas where the research output is insignificant. As a consequence, this may provide room for policymakers and funding opportunities. However, there is a challenge on the criteria to use to compare regions and territories/countries due to their particularities and differences. Nevertheless, disregarding all the other biases and evaluating the research output per million inhabitants on the topic, the top based on territories/countries are Canada for PCM implementation in a HEX (Query 1), and Austria for publications focussing on PCM at the evaporator (Query 2). However, under a wider perspective, i.e., regional/continental level, the highest research density is observed in Europe for both cases.

Expertise and experience of the major researchers may help in shaping future research perspectives. M.J. Hosseini, affiliated to Babol Noshirvani University of Technology in Iran, and Luisa F. Cabeza, affiliated to Universitat de Lleida in Spain, are the top authors of documents published on PCM implementation in a HEX, while Ryan Stephan, affiliated to NASA Jonhson Space Center in U.S.A, is the top author of documents published focussing on PCM at the evaporator. Based on the number of publications and duration of publications, the authors with documents published on PCM implementation in a HEX have more documents and more experience than the authors of documents on PCM at the evaporator. This highlights the literature gap in terms of experience and expertise in research for PCM implementation at the evaporator.

5. Conclusions

The paper studies the implementation of PCM in a HEX, a storage type which can be used in a wide range of applications. It analyses and provides an insight of the major research outputs on the topic, highlighting the research gaps while presenting the trends and links among the subtopics. From the papers obtained it can be concluded that the studies were carried out through both experimental and numerical approaches, and the trends seen suggest that the studies started with numerical modelling approaches and changed to the experimental studies recently. Solar energy was seen as the major heat source studied, although in recent days there is a change in trend to studies with more focus on waste heat recovery. Based on applications, it could be concluded that the trend in the studies started with heating and then followed with cooling. Although the new trend is on air conditioning and refrigeration applications, it was concluded that there is still a huge research gap when comparing to those focussing on cooling and heating applications.

Moreover, the study concludes that although there were a few publications about 40 years ago, only in the last 10 years the research on the topic of PCM implementation in a HEX has been important. It also concludes a research gap on studies towards PCM implementation at the evaporator, with the topic covering about 3.8% of the total number of publications. Most documents are published in reputable journals mainly as articles taking more than 60% for both queries. Moreover, the paper concludes a higher researchers expertise on research on the implementation of PCM in a HEX than on the PCM implementation at the evaporator. Researchers working on implementation of PCM at the evaporator have two or less documents, which may not be enough to claim experience on the particular topic. Based on their geographical distribution, Canada has the highest number of publications per million inhabitants for documents focusing on PCM implementation in a HEX (query 1), while Austria has the highest publications per million inhabitants for those focussing on PCM implementation at the evaporator (query 2). However, the research gap evaluated invites researchers to put more effort studying the topic in this new perspective.

Author contribution statement

Term/Author	Boniface Dominick Mselle	Gabriel Zsembinszki	Emiliano Borri	David Vérez	Luisa F. Cabeza*
Conceptualization	X	X	X	X	X
Methodology	X				X
Software					
Validation					
Formal analysis	X				
Investigation	X				
Resources					X
Data curation					X
Writing – Original draft	X				
Writing – Review & Editing		X	X	X	X
Visualization	X	X	X	X	
Supervision		X			X
Project administration					X
Funding acquisition					X

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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